CORRELATION BETWEEN THE MINIMUM VIRTUAL E-LAYER HEIGHT h'E AND THE 100-mb CIRCULATION

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THE PROBLEM

Study vlf and lf electromagnetic propagation mechanisms. Study the interrelationships of phenomena within the upper stratosphere and ionosphere which affect vlf and lf electromagnetic propagation and the extent to which variations of these phenomena may influence radio propagation. The study reported here examined the correlation between the minimum virtual E-layer height $h'E$ at Washington, D. C., and the stratospheric circulation over the eastern United States as a function of frequency and scale size of the circulation.

RESULTS

The minimum virtual E-layer height was found to be correlated with a particular type of large-scale circulation at the 100-mb level which has a period of 6.3 days. One of the ten circulation indices used to describe the 100-mb circulation was found to have predominant periods of 22 and 12 days. The predominant 12-day period appears to be controlling the correlation between the 100-mb circulation and $h'E$ at the 6.3-day period.

RECOMMENDATION

Correlate other ionospheric parameters with the circulation over larger regions of the world and at other pressure levels in the stratosphere or troposphere. Examine the physics of the relationship between $h'E$ and

the stratospheric circulation particularly with respect to the preference for $h'E$ to be related with certain circulation patterns which occur at certain periods.

ADMINISTRATIVE INFORMATION

Work was performed under SR 008 01 01, Task 7039 (NEL M2-3) and SF 011 05 11, Task 0558 (NEL M2-5) by members of the Radio Physics Division. The report covers intermittent work from 1 January 1958 to October 1962 and was approved for publication 22 January 1963.

The author expresses his appreciation to W. F. Moler and Dr. E. E. Gossard for their many suggestions and continued encouragements made during the progress of this study. Special thanks are extended to F. A. Sabransky who skillfully programmed the digital computer for the extensive calculations required and patiently altered these programs at my request. Without the careful work of R. O. Niemi in processing the data, considerable time would have been wasted. The careful preparation of the manuscript by Mrs. Eileen Jacobson is appreciated.

CONTENTS

ILLUSTRATIONS

INTRODUCTION

Many studies have been directed toward the common goal of determining the relationship between the tenuous ionosphere and the considerably denser atmosphere below, the stratosphere and troposphere.[1,2] (See list of references at end of report.) This study examines the relationship between the minimum virtual E-layer height $h'E$ and the 100-mb circulation, as a function of frequency and scale size of the circulation.

DEFINITION OF VARIABLES

$h'E$ is a function of the temperature structure of the atmosphere, solar radiation, atmospheric composition, and recombination rates. $h'E$ represents the lowest region of the ionosphere regularly measured and is essentially the height of the base of the E-layer, usually at about 100 km. $h'E$ at Washington, D. C., was chosen to represent the ionosphere and was taken from the CRPL-F series published by the National Bureau of Standards.[3] The height is tabulated in kilometers for every hour during the day when the layer exists. The error of $h'E$ was ±10 km before January 1956 and ±2 km afterwards. These large errors mask most variations thought to be of interest, but they were effectively reduced by taking a seven-hour average $\bar{h}'$ of $h'E$ centered around local noon each day. $\bar{h}'$ should be a better daily value of $h'E$ than a single hourly value.

It was decided to examine the relationship between the circulation on a constant pressure surface and $\bar{h}'$ because both are functions of the atmospheric temperature structure. The 100-mb winds at the seven stations shown in figure 1 were chosen to represent the 100-mb circulation.

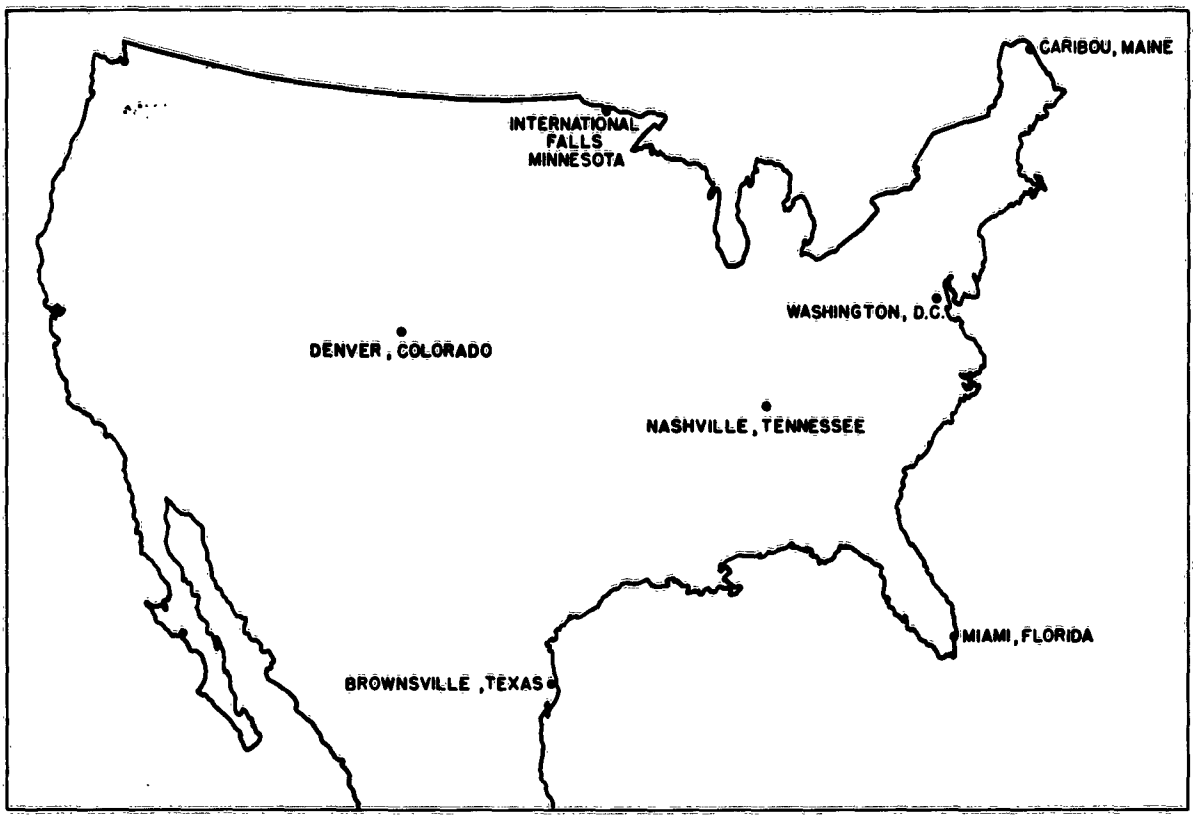

Figure 1. The seven stations used to describe the 100-mb circulation.

The number of stations was limited by the capacity of the computer for the statistical techniques chosen and the sample size of 2922 days. The station separation was selected so that relatively large- and small-scale sizes of the circulation would be included. The 100-mb winds were supplied by the National Weather Records Center for the eight-year period from March 1951 through February 1959.

The wind directions were given to 16 points of the compass, and the speeds were given in meters per second. The daily u- and v- components of the winds were computed for each station. The u-component is positive toward the east and the v-component is positive to the north.

The u- and v-components and $\bar{h}'$ were filtered to remove the annual cycle in the means. The filter response given in figure 2 shows that the amplitude reduction of the annual cycle was 0.05 while the amplitude of all variations with periods less then 100 days was unaffected. The sample size for the filtered data was 2722 days.

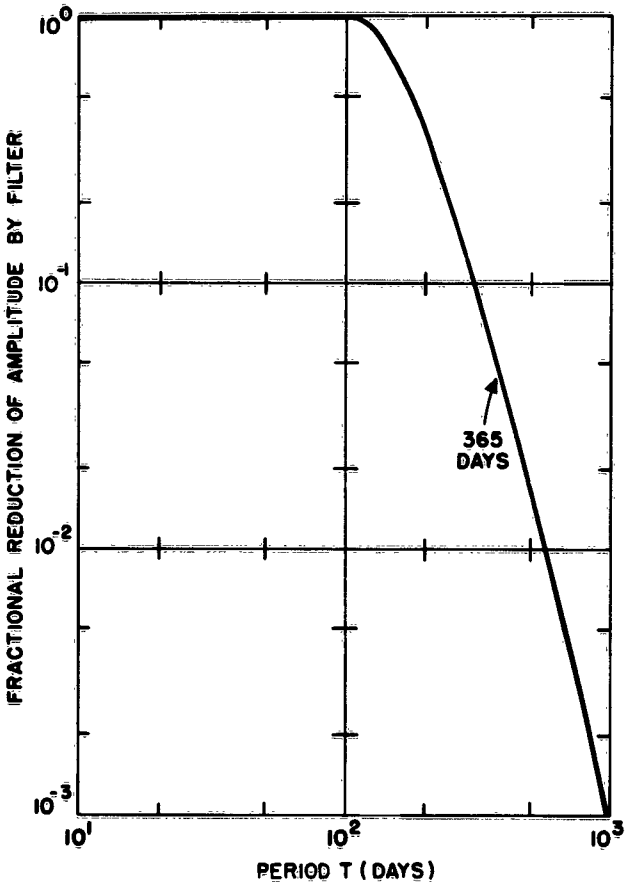

Figure 2. Response curve of the mathematical filter used to filter the data.

CIRCULATION INDICES

It is possible that $\bar{h}'$ is related to certain scale sizes of the 100-mb circulation at certain frequencies. A factor analysis technique developed in the Department of Meteorology at the Massachusetts Institute of Technology[4] was used to generate circulation indices which represent various scale sizes. The technique produces what has been labeled "empirical orthogonal functions." The technique was used to generate 14 uncorrelated time-varying weighting factors $q_i (1 \leq i \leq 14)$ of 14 corresponding orthogonal circulation patterns y_i from the correlated daily values of the seven pairs of filtered u- and v- components. This technique factorized the total variance of the correlated u- and v- components into a minimum number of orthogonal variables q_i's which contain a certain per cent of the total information. The q_i's and y_i's make up the "empirical orthogonal functions." Those q_i's containing little variance can generally be considered to be noise with respect to application in prediction and need not be correlated with $\bar{h}'$. Out of the 14 q_i's generated from the 14 u- and v- components, ten q_i's having the largest variance were required to contain 90 per cent of the information. The remaining four q_i's with small variance were eliminated in the correlation analysis. The first ten q_i's were the circulation indices used in this study. The distribution of the variance among the 14 q_i's is shown in figure 3.

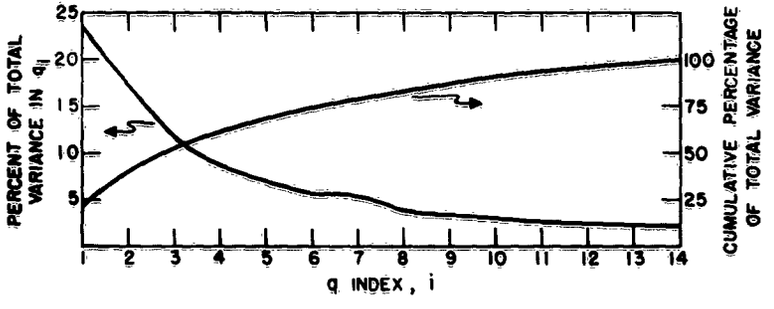

Figure 3. The distribution of the variance among the 14 q_i's.

The u- and v- components, the q_t's, and the y_t's are related according to the matrix equation:

$$\begin{pmatrix} u_{11} \cdots u_{17}\, v_{11} \cdots v_{17} \\ \cdots \\ u_{n1} \cdots u_{n7}\, v_{n1} \cdots v_{n7} \end{pmatrix} = \begin{pmatrix} q_{11} \cdots q_{1,10} \\ \cdots \\ q_{n1} \cdots q_{n,10} \end{pmatrix} \begin{pmatrix} u y_{11} & \cdots u y_{17} & v y_{11} & \cdots v y_{17} \\ \cdots & & & \\ u y_{10,1} \cdots u y_{10,7} & v y_{10,1} & \cdots v y_{10,7} \end{pmatrix} \quad (1)$$

where n is 2722 days. Each row in the u-v matrix is the set of u- and v- components for the seven stations on day t. Each column i in the q-matrix is a function of time t and is orthogonal to the other nine columns. Each row i in the y-matrix is a function of space and is orthogonal to the other nine rows. The u- and v-components for station j on day t are

$$u_{tj} = \sum_{i=1}^{10} q_{ti}\, u y_{ij} \quad (2a)$$

$$v_{tj} = \sum_{i=1}^{10} q_{ti}\, v y_{ij} \quad (2b)$$

From equation 2 the direction and magnitude of all winds can be determined with the noise removed. If all q_t's are zero except when $t = s$, then

$$|\vec{V}| = \left| q_{ts} \left(u y^2_{sj} + v y^2_{sj} \right)^{\frac{1}{2}} \right| \quad (3a)$$

$$\tan\theta_j = \frac{v y_{sj}}{u y_{sj}} \quad (3b)$$

When q_s is negative, the wind direction is opposed to the direction given by equation 3b.

Figure 4 shows the first ten orthogonal functions of space y_t's derived from equations 3a and 3b. The isopleths are relative height contours in feet for q_s equal to 1. It is noticed that, in general, the scale size of the circulation decreases as t increases. This agrees with earlier studies. It is now evident that a correlation between $\bar{h}'$ and the q_t's, the weighting factors of the y_t's, is a correlation between $\bar{h}'$ and various scale sizes of the 100-mb circulation.

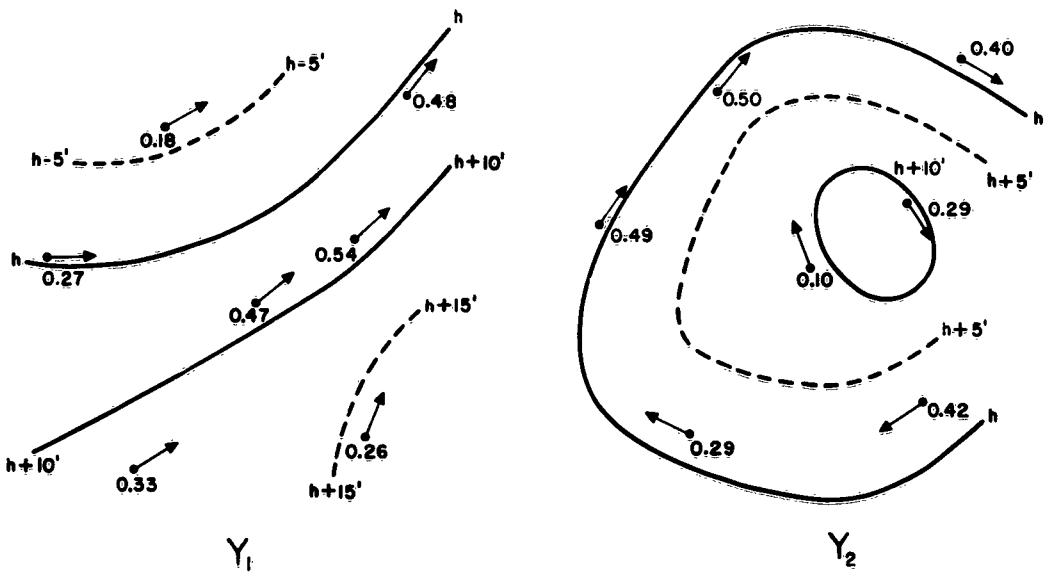

Figure 4. The first ten orthogonal functions of space. The isopleths are relative height contours of the 100-mb surface when q_t = 1. The wind speeds given at each station are in meters per second.

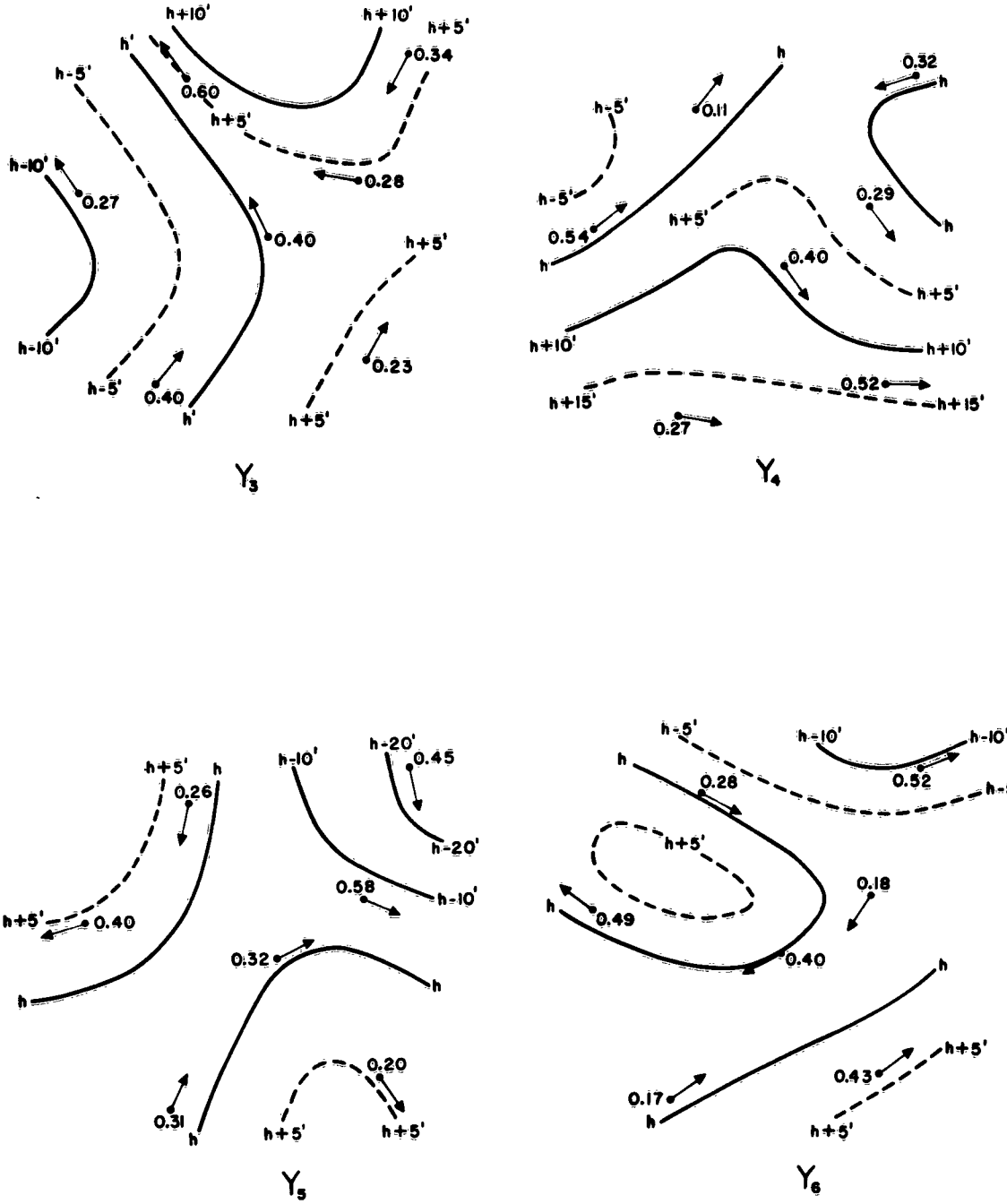

Figure 4. (Continued)

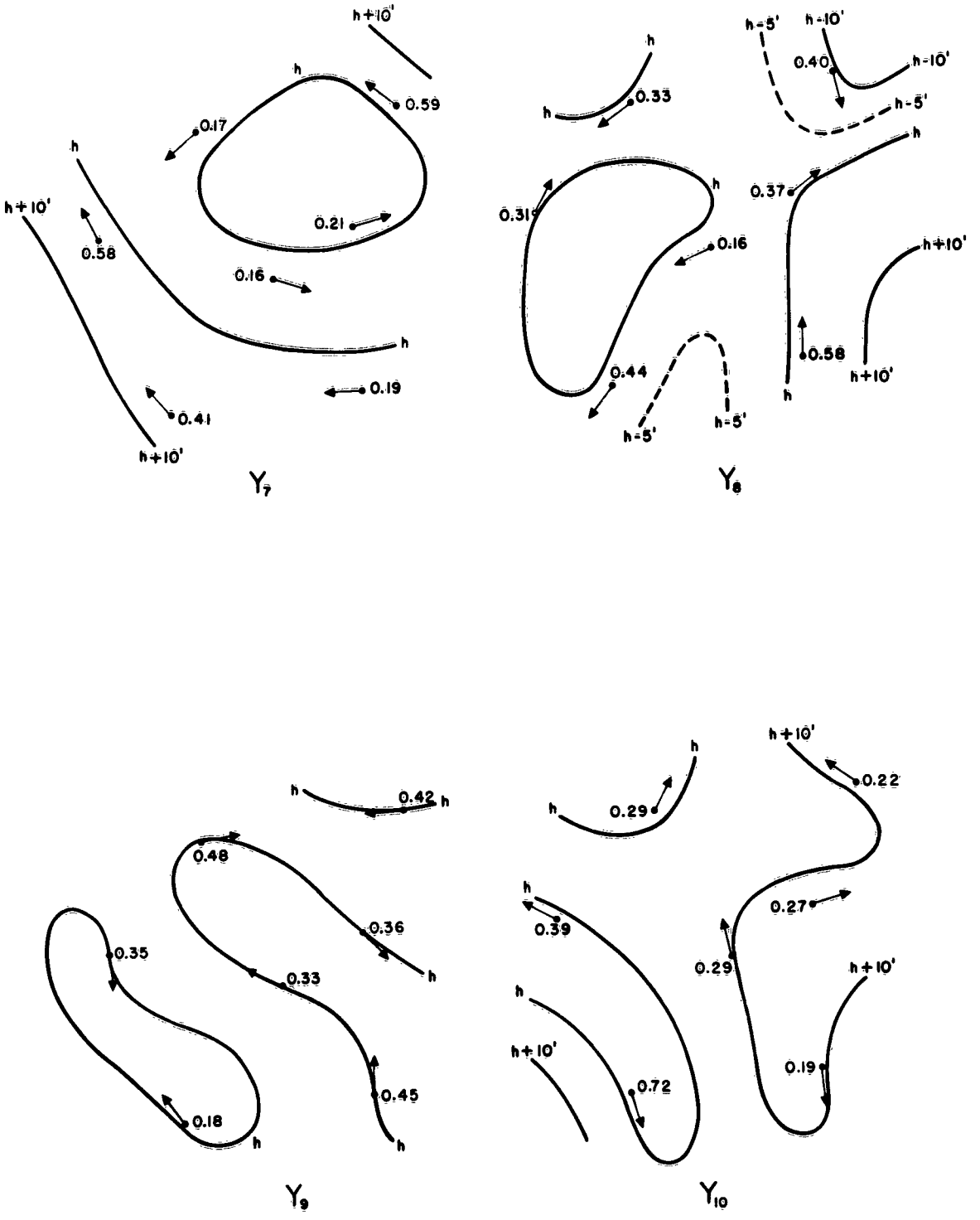

Figure 4. (Continued)

POWER SPECTRUM

If the relationship between $\bar{h}'$ and the q_i's is to be examined as a function of frequency or period, as well as a function of scale size, cross-spectrum analysis between $\bar{h}'$ and the q_i's is required. Cross-spectrum analysis gives the square of the correlation, the coherence CH, as a function of period, and the phase lag τ between correlated frequencies. Two time series can be related at certain frequencies which are not predominant in either time series. An examination of the power spectrum of $\bar{h}'$ and the q_i's will indicate the relative amplitudes of all frequencies present in the time series.

Figure 5 shows the unnormalized power spectra $U(n)$ of $\bar{h}'$ and the first ten q_i's as a function of the ordinate number n for n between 0 and 80. The frequency interval between ordinates is equal to 4×10^{-3} cycles per day. Thus the periods range from infinity to 3.3 days. There are 43 degrees of freedom in each estimate of $U(n)$. All power spectra generally show a concentration of energy at low frequencies and a gradual decrease of energy as frequency increases, a common feature of meteorological data. The concentration of variance in the lower order q_i's should be noted.

No predominant periodicities are present in the power spectra except the spectrum for q_2. There are two very significant periodicities in q_2 as indicated by the 90 per cent confidence limits.* The two predominant periods are 12.5 and 22.2 days. A power spectrum of q_2 with 20 degrees of freedom, which is not shown, indicates an even greater level of significance at the two periods and places the predominant periods at 12.5 and 21.7 days. The presence of two predominant periodicities in q_2 implies

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*The true value of $U(n)$ will lie within the limits given in figure 5 for 90 per cent of the time when there are 43 degrees of freedom.

that y_2 varies every 12.5 and 22 days from a cyclonic to an anticyclonic circulation as q_2 goes from a negative to a positive value. The amplitudes of the two predominant periods are, of course, additive. No pressure pattern motion is implied because y_2 is a fixed pattern of space. If y_2 is part of a wave pattern around the Northern Hemisphere, then y_2 is part of a standing wave pattern. y_2 extends about 3000 km in the east-west direction. If y_2 is one-half a 6000-km wave, then y_2 suggests a wave number of 5. Based on a numerical experiment, Phillips[5] predicted that the wave number 5 would have an eastward velocity of 1800 km/day. It is interesting to note that the beat between a 12.5 and 21.7 day period is a 29.5 day period, which is almost a lunar cycle.

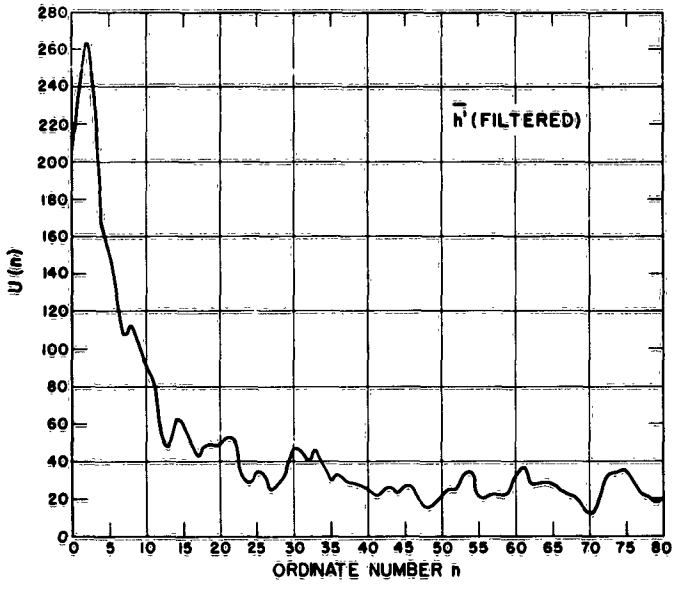
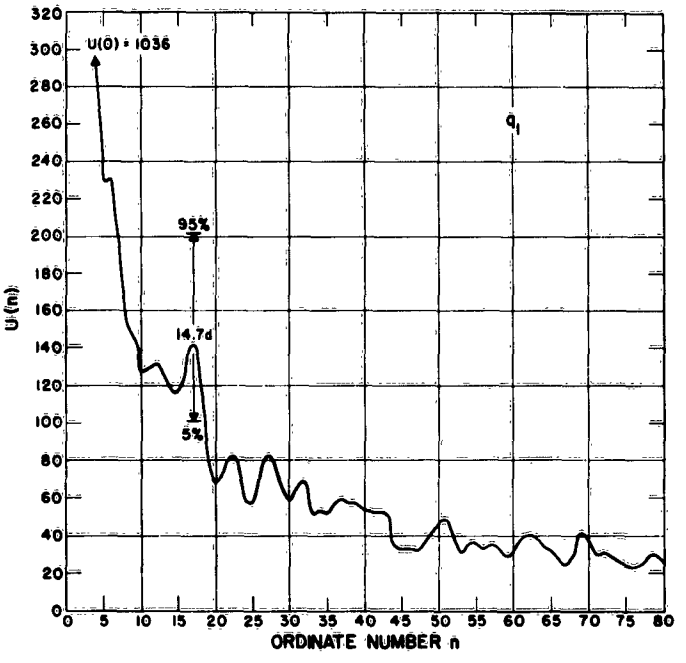
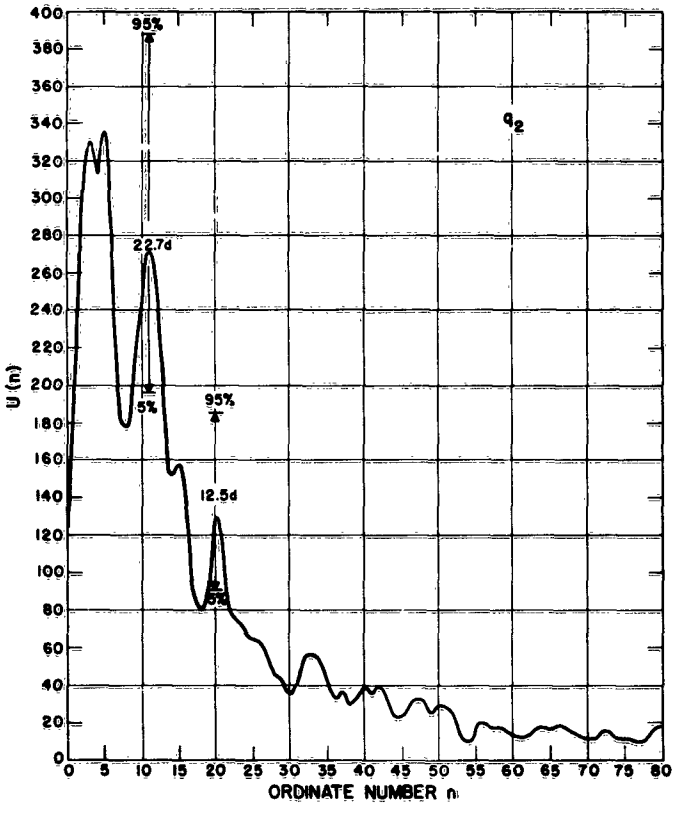


Figure 5. The power spectra of $\bar{h}'$ and the first ten orthogonal functions of time with 43 degrees of freedom. The frequency interval between the ordinates is 4 x 10^{-3} cycles/day. The amplitudes of the low frequencies have been reduced by filtering the wind components (see fig. 2).





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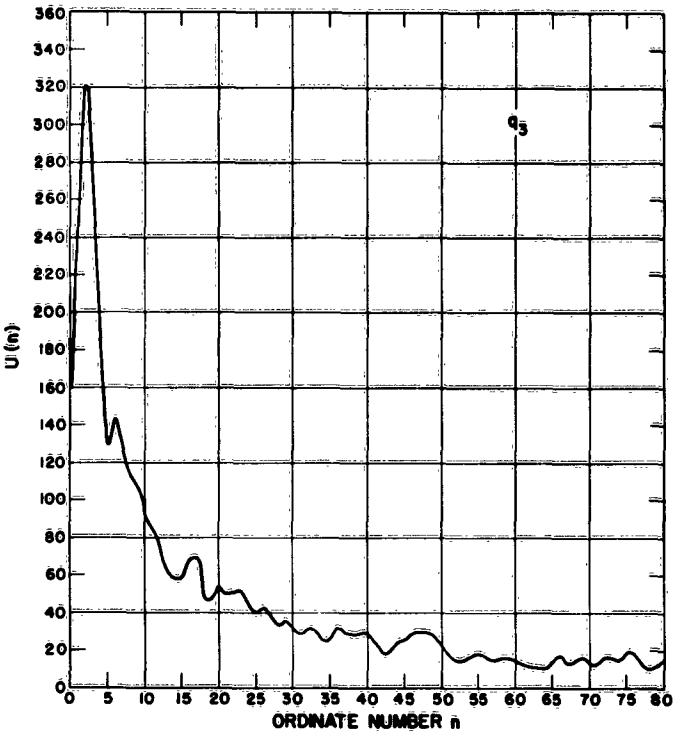

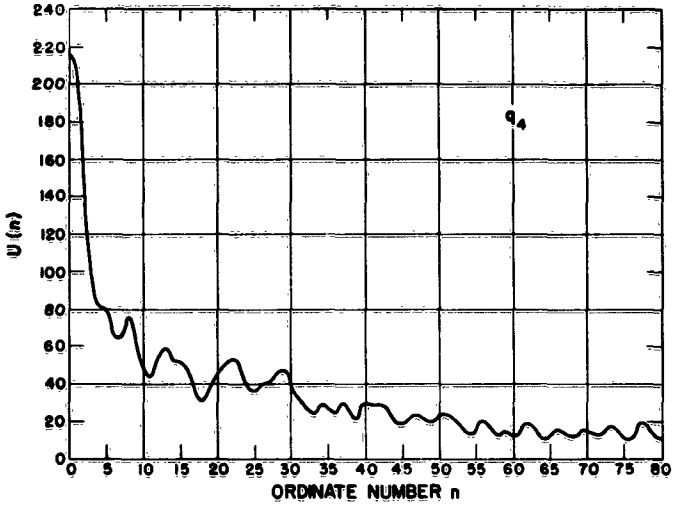

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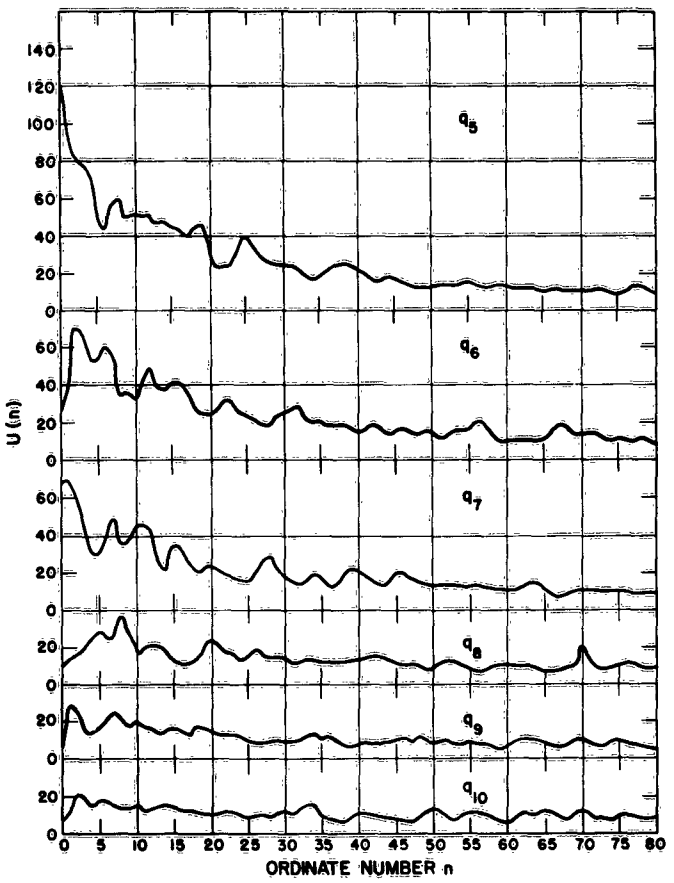

Figure 5. (Continued)

CORRELATION BETWEEN h' AND THE 100-mb CIRCULATION

Figure 6 shows the coherence CH between h' and the first ten q_i's for periods between 250 and 5 days. The CH between two series of eight-digit random numbers having the same degrees of freedom is shown for comparison. Although independence between the q_i's at all periods has not been established, the CH's of all ten q_i's were added to give the total CH, as shown at the bottom as CH_T. If the ten q_i's are orthogonal at all periods, then CH_T is equivalent to the total reduction in variance. CH_T can be used as a guide in determining the most important periods until the degree of independence between the q_i's has been established.

There are five predominant peaks in the ten CH functions in figure 6. Two peaks occur with q_2, one occurs with q_5, and two occur with q_8. q_2 is related to $\bar{h}'$ at a period of about 13 or 14 days and at a period of 6.3 days. The shape of the peak regions in CH for q_5 and q_8 are surprisingly similar between the 6.3 and 6.6 day period. q_8 also has a peak in CH at a period of 17.9 days. The probability that the five peak values of CH could happen by chance ranges from 0.165 to 0.035 as shown in figure 6. Although the five CH peaks are not highly significant, an examination of the relationship between $\bar{h}'$, q_2, q_5, and q_8 at a period of 6.3 days was thought to be valuable primarily because the relationship apparently involves the fundamental periodicity of 12.5 days found to be predominant in q_2. CH_T also indicates that the relationship between $\bar{h}'$ and the 100-mb level is singificant at a period of 6.3 days. The remaining part of this paper will be an examination of the relationship between $\bar{h}'$, q_2, q_5, and q_8 at a period of 6.3 days.

The phase lag τ in days for q_2, q_5, and q_8, relative to $\bar{h}'$ for a period of 6.3 days, is 2.4, 4.4, and 6.2 days respectively. The 90 per cent confidence limits of these

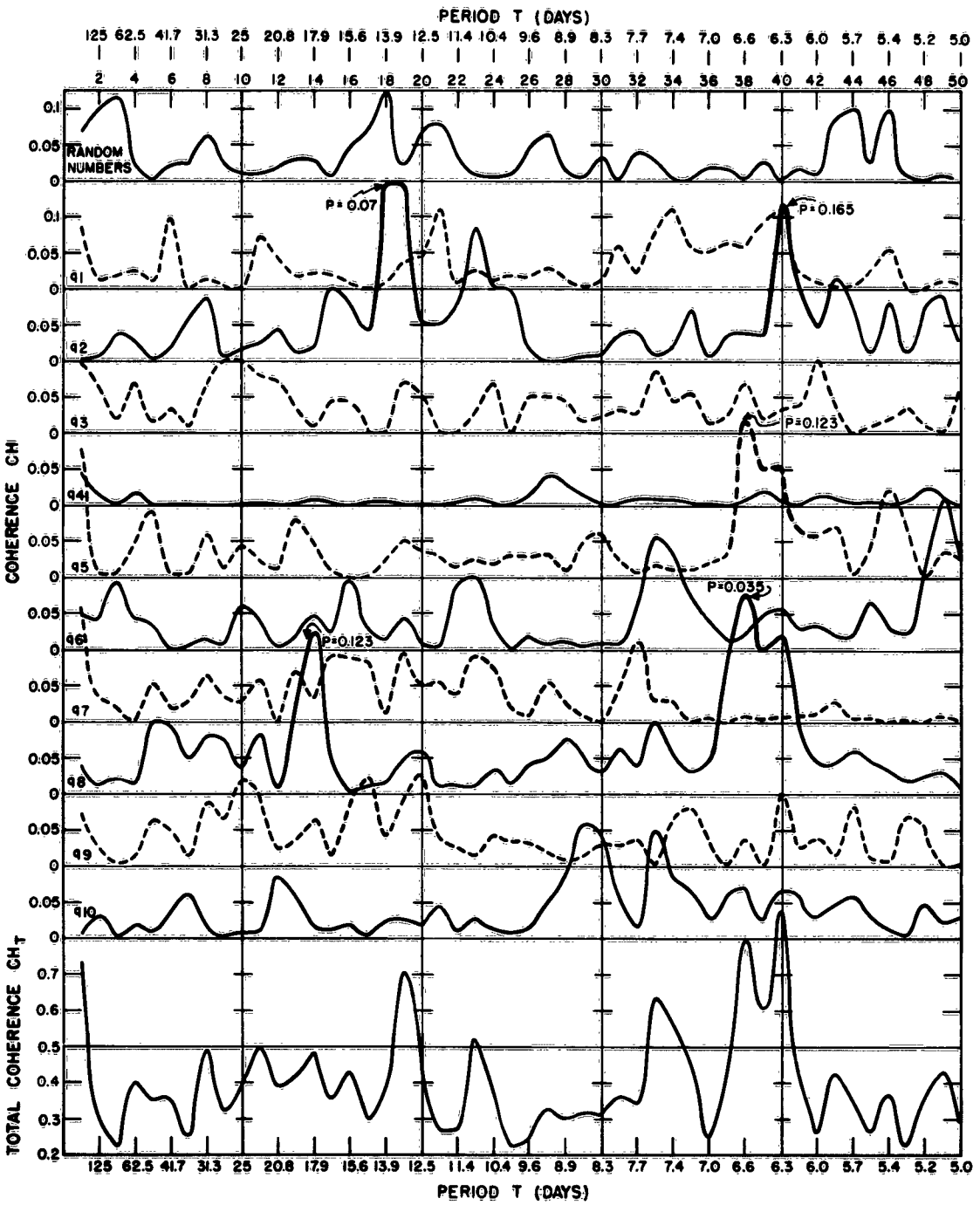

Figure 6. The coherence CH between the first ten q_i's and $\bar{h}$'as a function of the ordinate number n or period. The most significant regions of CH have been accented.

lags are ±0.7, ±0.8, and ±0.7 days respectively.* None of the 90 per cent limits overlap. q_8 can be assumed to be in phase with $\bar{h}'$ because the lag of 6.2 days is essentially equal to the period of 6.3 days. Assuming that the phase lags are 2, 4, and 0 days for q_2, q_5, and q_8, respectively, and that the relative amplitudes at a period of 6.3 days are given by the power spectra, the cyclical pressure pattern related to $\bar{h}'$ can be constructed.

Figure 7 gives the cyclic pressure pattern related to $\bar{h}'$ as specified by q_2, q_5, and q_8 for an even six-day period instead of a 6.3-day period. The isopleths in figure 7 are relative heights of the 100-mb surface for the relative wind speeds shown. On Day 1 (4) a trough (ridge) extends in the east-west direction. On Day 2 (5) the trough (ridge) begins to tilt in a NE-SW direction. On Day 3 (6) the southern part of the trough (ridge) moves eastward, while the northern position remains about stationary, but the general NE-SW tilt is conserved. The maximum (minimum) in $\bar{h}'$ occurs on Day 3 (6). The pressure trough on Day 3, when h' peaks, is quite similar to a wave on a frontal surface. Apparently $\bar{h}'$ is associated with NE-SW oriented ridges and troughs on the 100-mb surface, which occur about every six days. The maximum of $\bar{h}'$ occurs when q_2 is negative and increasing; that is, when the cyclonic flow is decreasing and being replaced by an anticyclonic flow. The phase lag between $\bar{h}'$ and q_2 at a period of about 13 days is about 10 days, which indicates that the maximum of $\bar{h}'$ occurs when q_2 is about zero and decreasing in magnitude.

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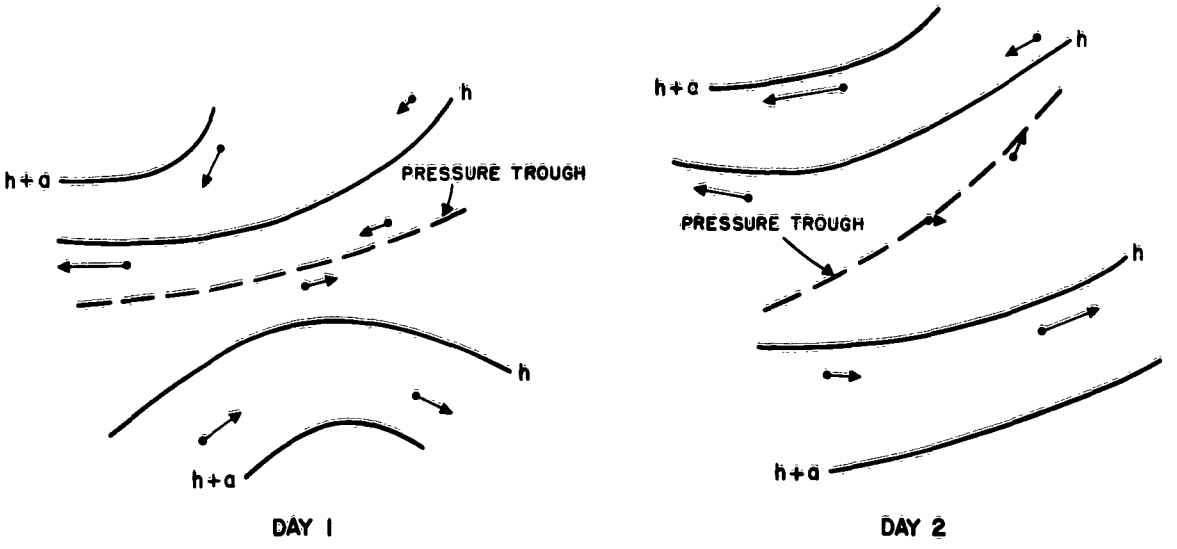
*The true value of τ will lie within the stated limits 90 per cent of the time when there are 43 degrees of freedom.



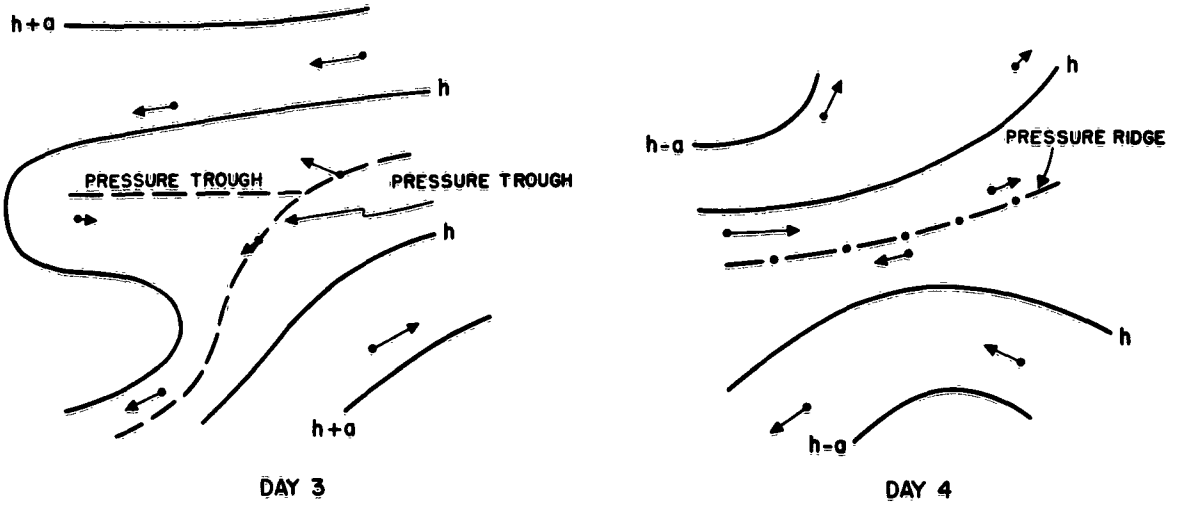
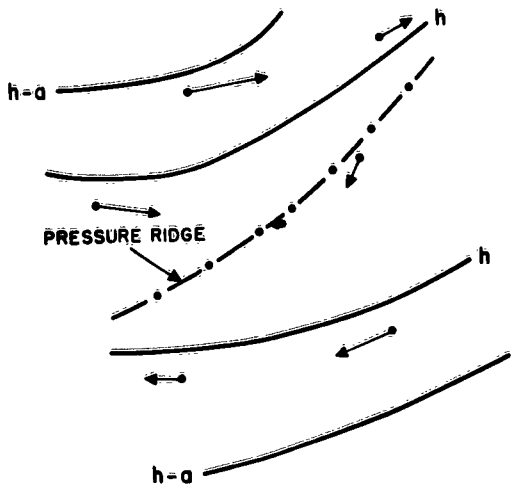
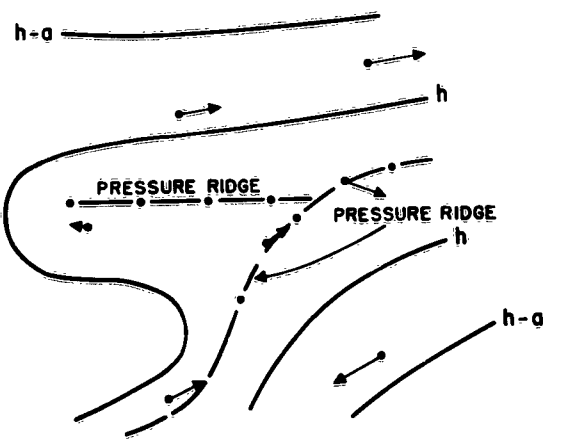


Figure 7. The six-day cyclic 100-mb pressure pattern that is related to $\bar{h}'$. The isoplethe are relative height contours of the 100-mb surface.



DAY 5



DAY 6

Figure 7. (Continued)

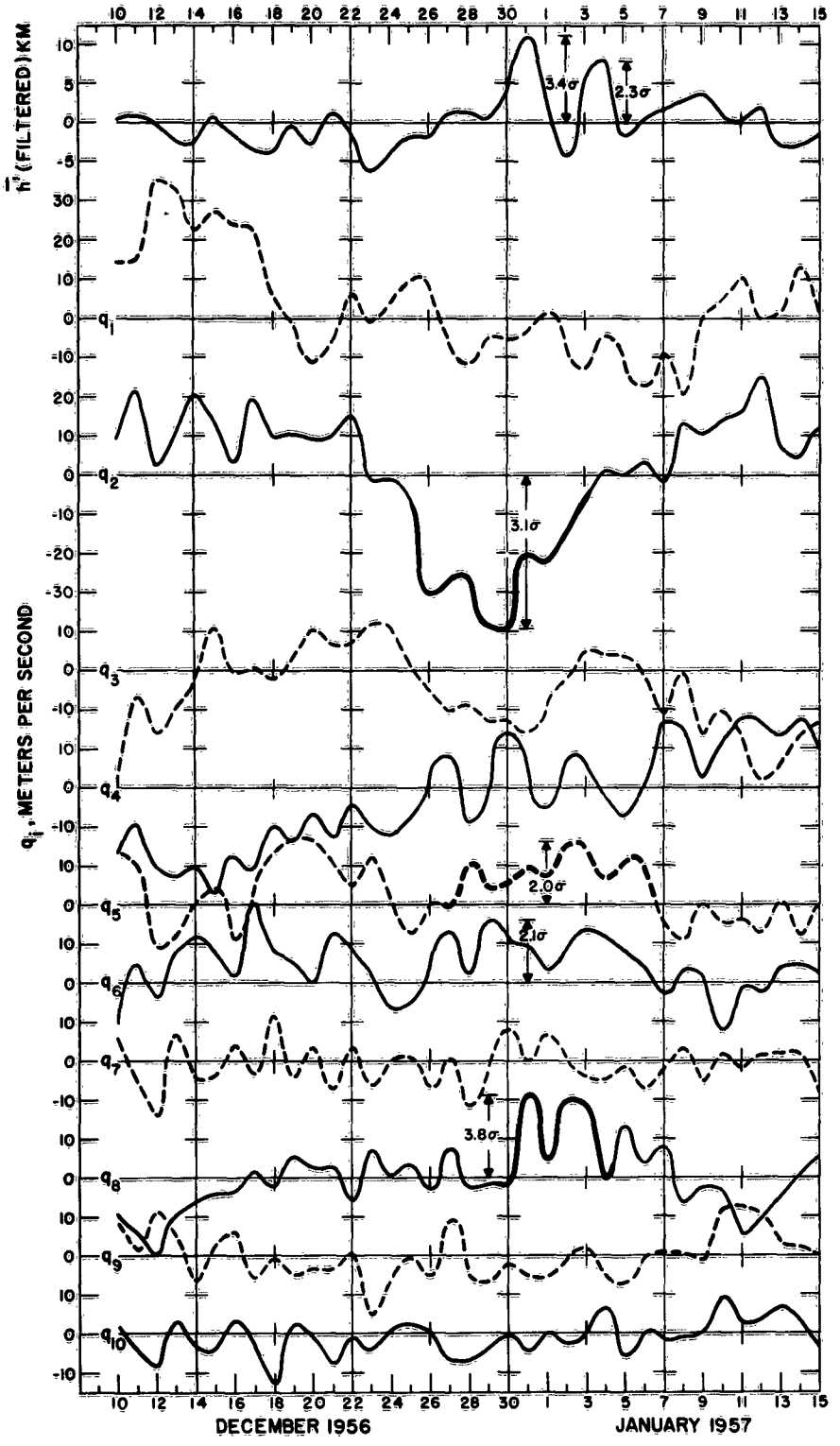
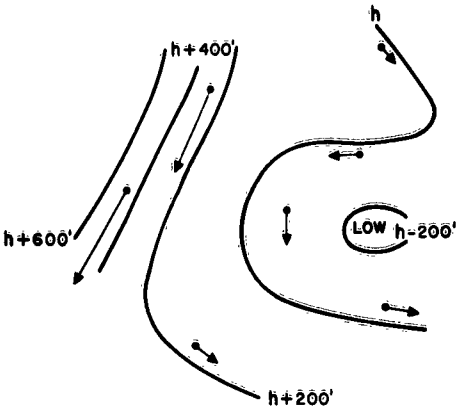
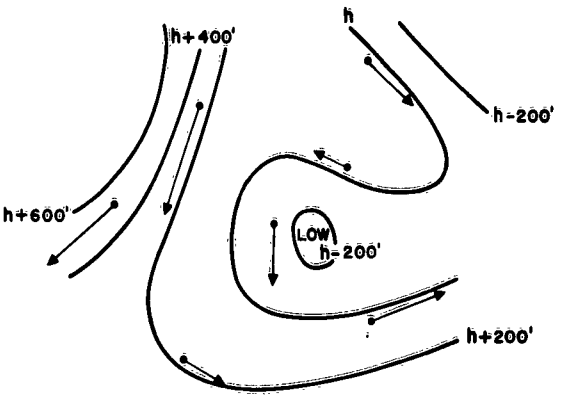


Figure 8. Variations of $\bar{h}'$ and the first ten q_i's from 10 December 1956 to 15 January 1957.



100 - mb Q - CIRCULATION
DECEMBER 28, 1956



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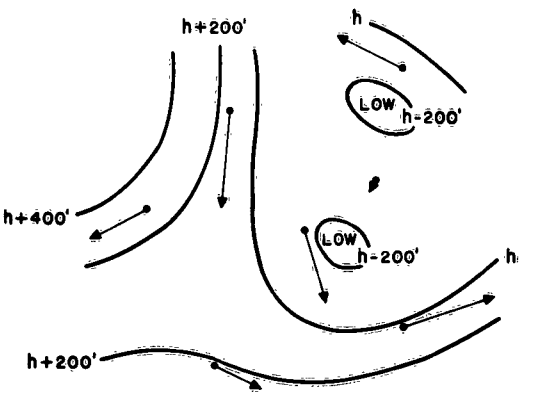

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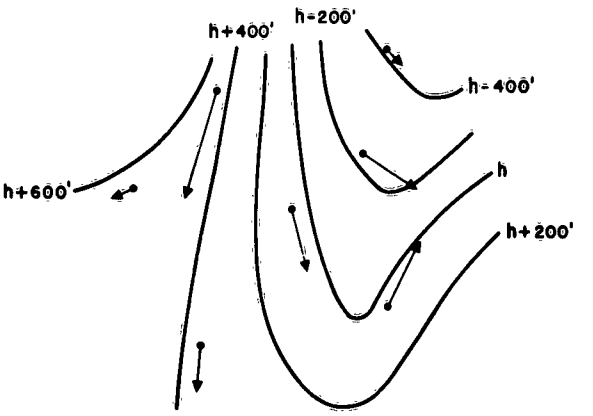

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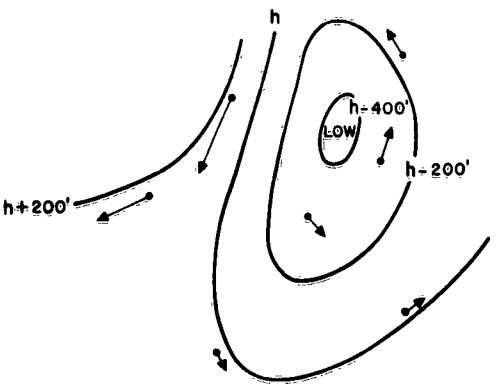
DECEMBER 31, 1956



100 - mb Q - CIRCULATION
JANUARY 1, 1957

Figure 9. The 100-mb pressure pattern from 28 December 1956 to 1 January 1957 according to the first ten q_i's given in figure 8. The isopleths are relative height contours for the 100-mb surface.

COHERENCE BETWEEN THE CIRCULATION INDICES

To determine the use of $CH_{\bar{I}}$ as an indicator of the total reduction in variance, CH between q_2 and q_5, q_2 and q_8, and q_5 and q_8 were determined. These CH's are shown in figure 10. It should be noted that relatively large peaks occur in CH at a period of about 6.3 days, particularly between q_2 and q_8 and between q_5 and q_8. It should be noted that neither q_2, q_5, nor q_8 has a predominant periodicity at a period of 6.3 days. The peak between q_5 and q_8 has a p-value of 0.052 and is more significant than the other peaks. The similarity in the shape of the CH curves of $\bar{h}'$-q_5 and $\bar{h}'$-q_8 at a period of about six days probably resulted from the correlation between q_5 and q_8 at about a six-day period. Thus, it appears that $CH_{\bar{I}}$ can be used only to indicate the most important regions where $\bar{h}'$ and the 100-mb circulation are related.

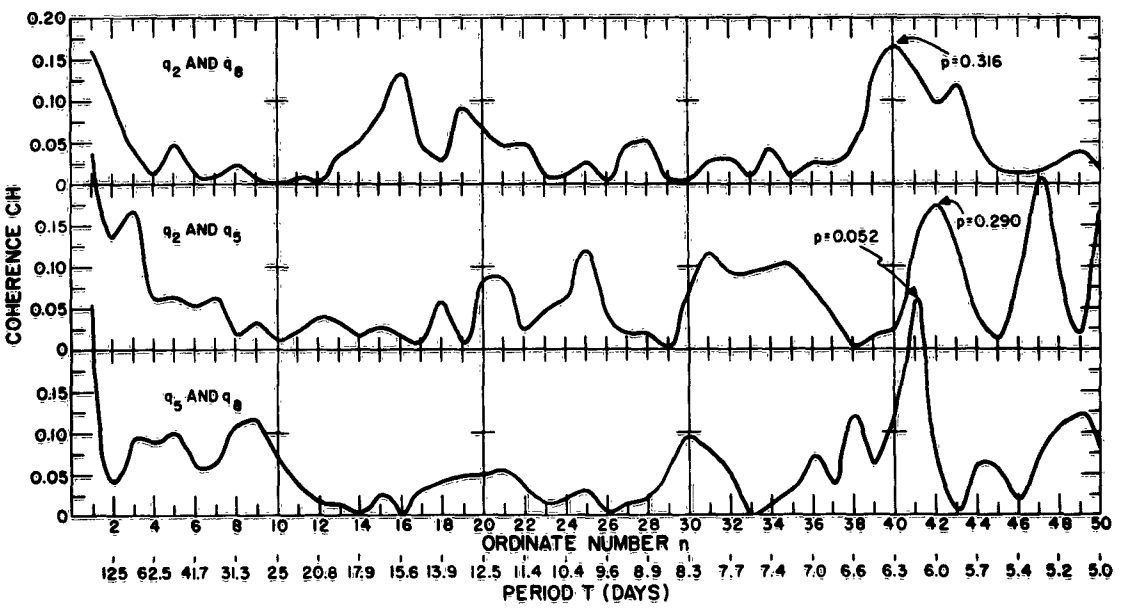


Figure 10. The coherence CH between q_2 and q_5, q_2 and q_5, and q_5 and q_8.

CONCLUSIONS

From the standpoint of statistical significance, the most important result of this study is the detection of two predominant periodicities in one of the ten orthogonal indices used to describe the 100-mb circulation. These predominant periods occur in q_2 and are 22 and 12.5 days. Apparently $\bar{h}'$ and the 100-mb circulation are only related at periods of about 18, 13, and 6 days. The correlation between $\bar{h}'$ and q_8 at an 18-day period was not examined in this study. The mechanisms producing the 22 and the 12.5 day period in q_2 may be different because $\bar{h}'$ is not related to the 100-mb circulation at the 22-day period while it is at the 12.5-day period. It is thought that the statistically deduced pressure pattern related to $\bar{h}'$ at a period of about 6.3 days is significant although the significance of the CH peaks at a period of 6.3 days is not high because the 6.3-day pattern is apparently controlled by the predominant 12.5-day period.

RECOMMENDATION

Correlate other ionospheric parameters with the circulation over larger regions of the world and at other pressure levels in the stratosphere or troposphere. Examine the physics of the relationship between $h'E$ and the stratospheric circulation particularly with respect to the preference for $h'E$ to be related with certain circulation patterns which occur at certain periods.

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